Pointers, Alias & ModRef Analyses

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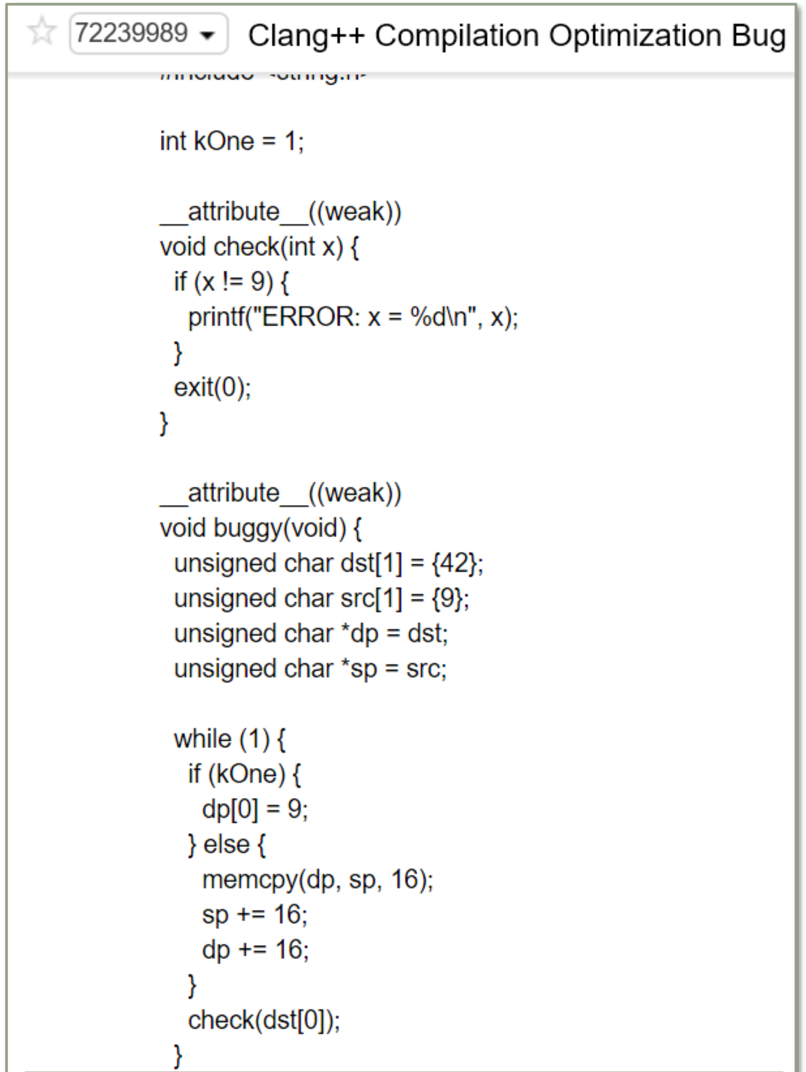
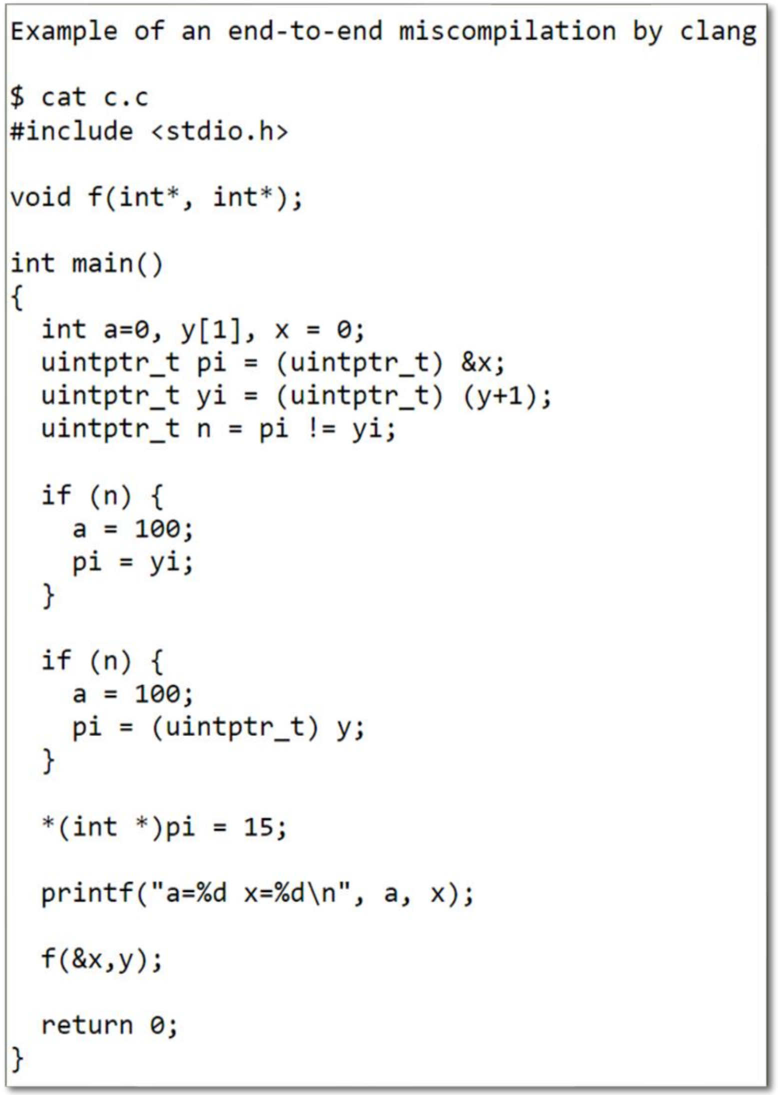


☆ 72239989 ▾ Clang++ Compilation Optimization Bug

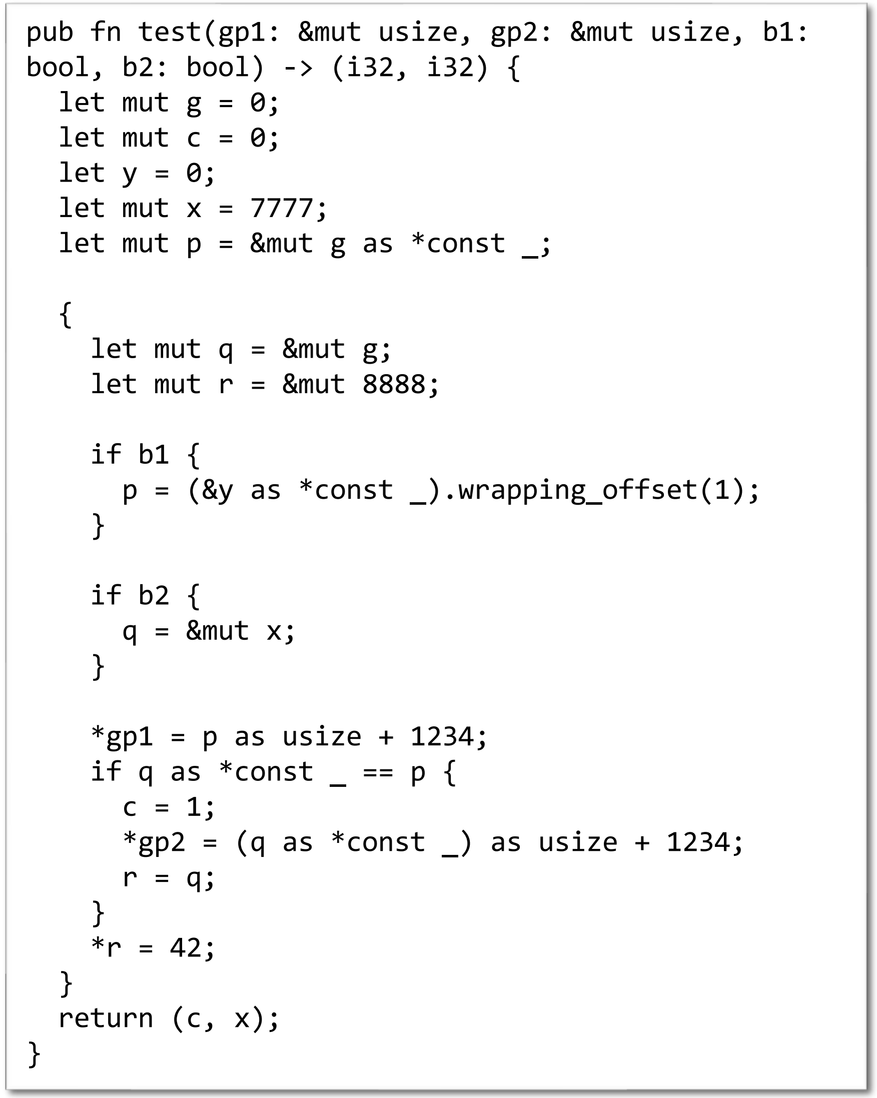
```
#include <string.h>

int kOne = 1;

__attribute__((weak))
void check(int x) {
  if (x != 9) {
    printf("ERROR: x = %d\n", x);
  }
  exit(0);
}

__attribute__((weak))
void buggy(void) {
  unsigned char dst[1] = {42};
  unsigned char src[1] = {9};
  unsigned char *dp = dst;
  unsigned char *sp = src;

  while (1) {
    if (kOne) {
      dp[0] = 9;
    } else {
      memcpy(dp, sp, 16);
      sp += 16;
      dp += 16;
    }
    check(dst[0]);
  }
```

PR36228: miscompiles Android: API usage mismatch between AA and AliasSetTracker

PR34548: incorrect Instcombine fold of inttoptr/ptrtoint



```
Example of an end-to-end miscompilation by clang

$ cat c.c
#include <stdio.h>

void f(int*, int*);

int main()
{
  int a=0, y[1], x = 0;
  uintptr_t pi = (uintptr_t) &x;
  uintptr_t yi = (uintptr_t) (y+1);
  uintptr_t n = pi != yi;

  if (n) {
    a = 100;
    pi = yi;
  }

  if (n) {
    a = 100;
    pi = (uintptr_t) y;
  }

  *(int *)pi = 15;

  printf("a=%d x=%d\n", a, x);

  f(&x,y);

  return 0;
}
```



```
pub fn test(gp1: &mut usize, gp2: &mut usize, b1:
bool, b2: bool) -> (i32, i32) {
  let mut g = 0;
  let mut c = 0;
  let y = 0;
  let mut x = 7777;
  let mut p = &mut g as *const _;

  {
    let mut q = &mut g;
    let mut r = &mut 8888;

    if b1 {
      p = (&y as *const _).wrapping_offset(1);
    }

    if b2 {
      q = &mut x;
    }

    *gp1 = p as usize + 1234;
    if q as *const _ == p {
      c = 1;
      *gp2 = (q as *const _) as usize + 1234;
      r = q;
    }
    *r = 42;
  }
  return (c, x);
}
```

Safe Rust program miscompiled by GVN

Pointers ≠ Integers

What’s a Memory Model?

```
char *p = malloc(4);
char *q = malloc(4);

q[2] = 0;

p[6] = 1;

print(q[2]);
```

1) When is a memory operation UB?

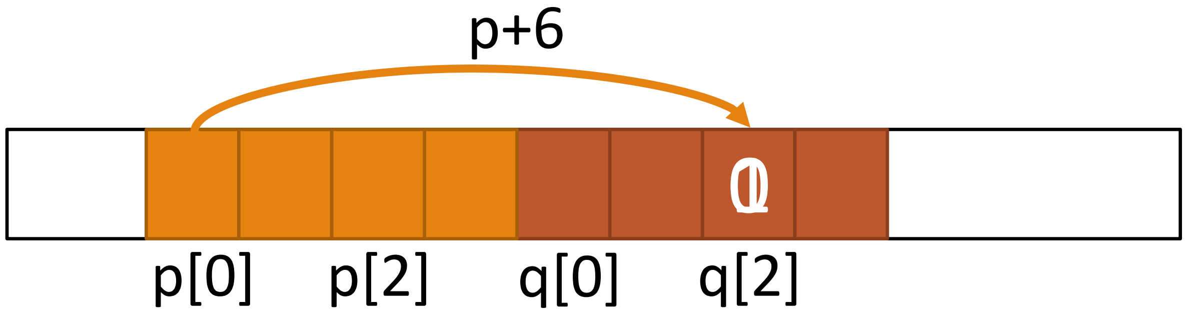
2) What’s the value of a load operation?

UB?

0 or 1?

Flat memory model

```
char *p = malloc(4);
char *q = malloc(4);

q[2] = 0;

p[6] = 1;      Not UB

print(q[2]);  print(1)
```



Simple, but inhibits optimizations!

Two Pointer Types

- Logical Pointers, which originate from allocation functions (malloc, alloca, …):

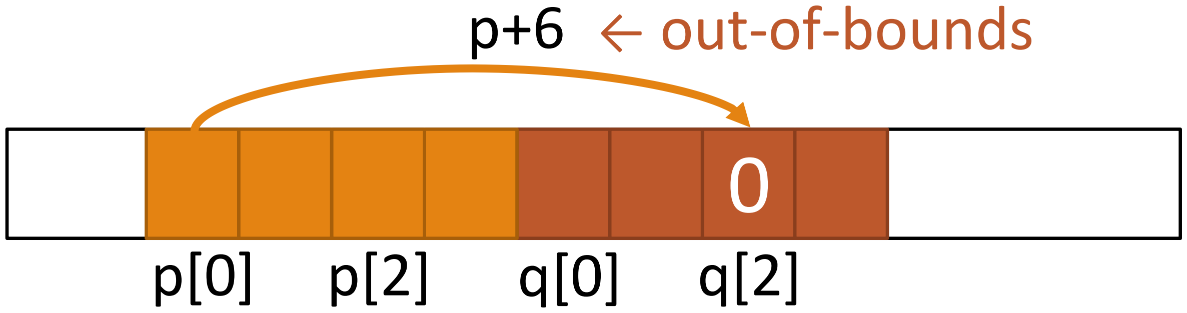
```c
char *p = malloc(4);
char *q = p + 2;
char *r = q - 1;
```

- Physical Pointers, which originate from inttoptr casts:

```c
int x = ...;
char *p = (char*)x;
char *q = p + 2;
```

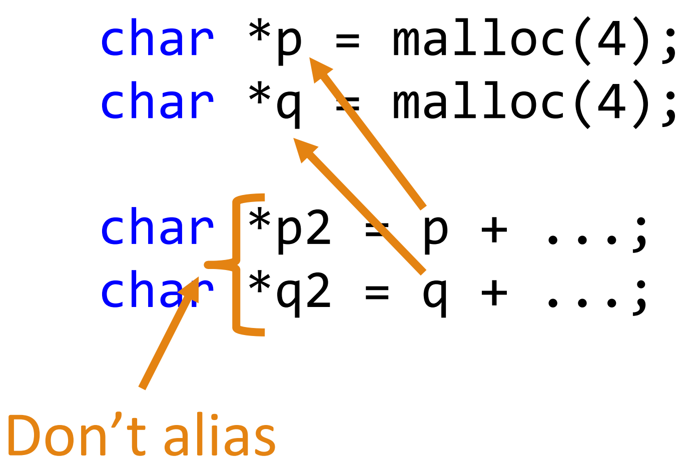
Logical Pointers: data-flow provenance

```
char *p = malloc(4);
char *q = malloc(4);
char *q2 = q + 2;
char *p6 = p + 6;

*q2 = 0;
*p6 = 1;  UB

print(*q2);  print(0)
```



Pointer must be inbounds of object found in use-def chain!

Logical Pointers: simple NoAlias detection



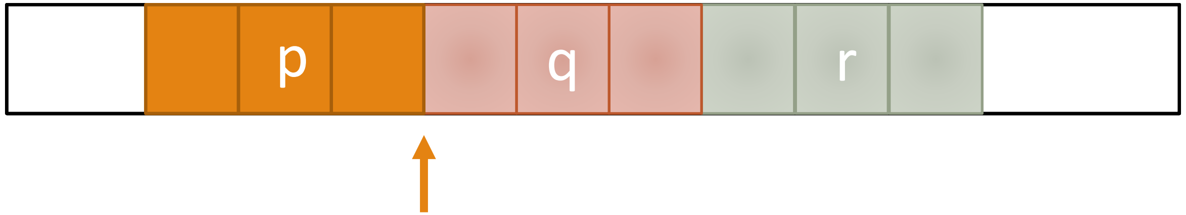
```
char *p = malloc(4);
char *q = malloc(4);

char *p2 = p + ...;
char *q2 = q + ...;
```

Don’t alias

If 2 pointers are derived from different objects, they don’t alias!

Physical Pointers: control-flow provenance

```
char *p = malloc(3);
char *q = malloc(3);
char *r = malloc(3);
int x = (int)p + 3;
int y = (int)q;

if (x == y) {
   *(char*)x = 1; // OK
}


*(char*)x = 1; // UB
```



Observed address of p (data-flow)

Observed p+n == q (control-flow)

Can’t access r, only p and q

Only p observed; p[3] is out-of-bounds

Physical Pointers: p ≠ (int*)(int)p

```
char *p = malloc(4);
char *q = malloc(4);
int x = (int)p + 4;
int y = (int)q;

*q = 0;

if (x == y)
  *(char*)y = 1;

print(*q); // 0 or 1
```

Ok to replace with q

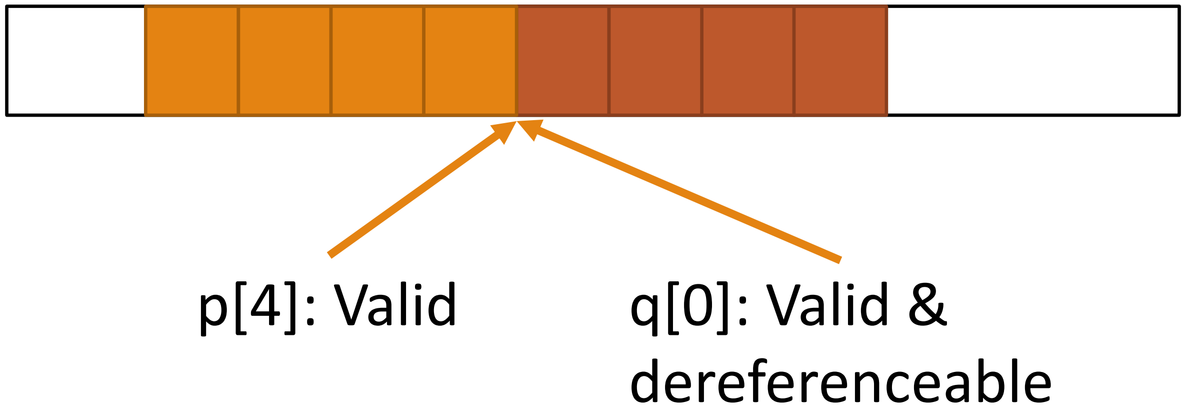
GVN

```
char *p = malloc(4);
char *q = malloc(4);
int x = (int)p + 4;
int y = (int)q;

*q = 0;

if (x == y)
  *(char*)x = 1;

print(*q); // 0 or 1
```

Not ok to replace with ‘p + 4’

Physical Pointers: p+n and q

```
int x = (int)q; // or p+4

*(char*)x = 0; // q[0]
*(((char*)x)+1) = 0; // q[1]
*(((char*)x)-1) = 0; // p[3]
```



At inttoptr time we don’t know which objects the pointer may refer to (1 or 2 objects).

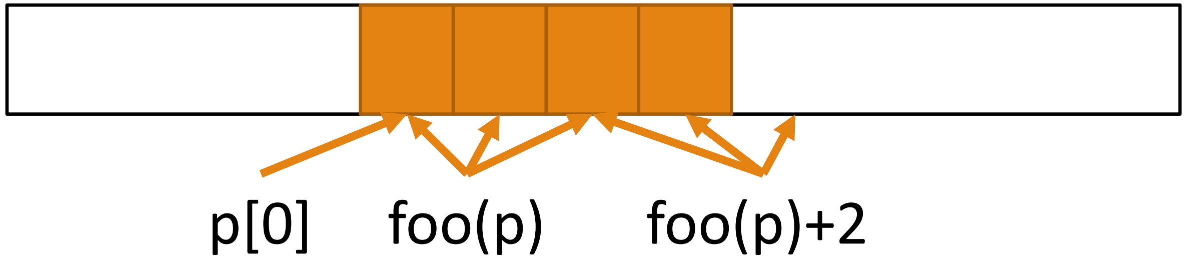
GEP Inbounds

```
%q = getelementptr inbounds %p, 4
```

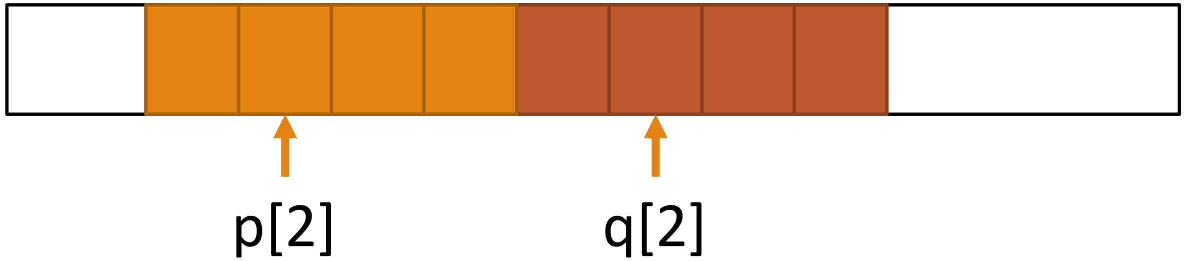
Both %p and %q must be inbounds of the same object

```
char *p = malloc(4);
char *q = p +inbounds 5;

*q = 0; // UB
```

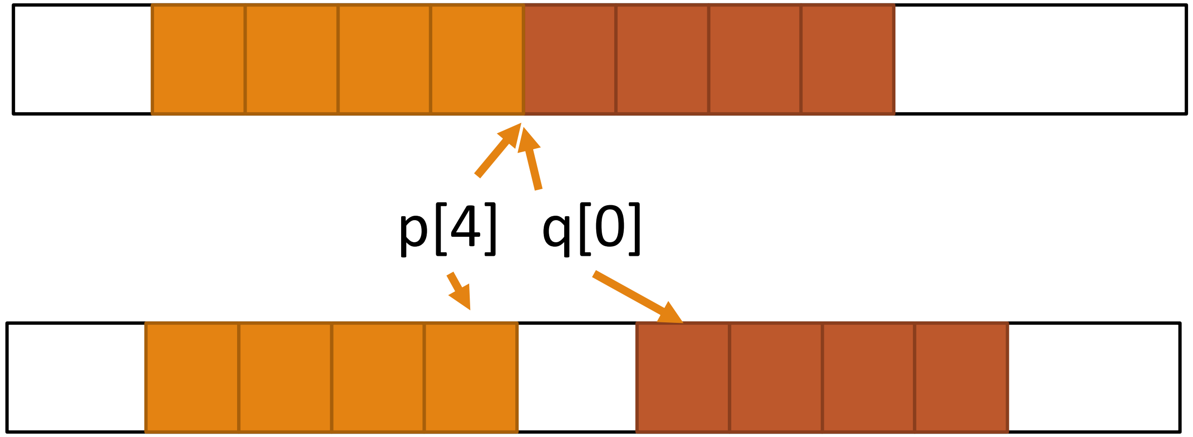
```
char *p = malloc(4);
char *q = foo(p);
char *r = q +inbounds 2;
p[0] = 0;
*r = 1;
```



No Layout Guessing



Dereferenceable pointers:
p+2 == q+2 is always false



Valid, but not dereferenceable pointers:
p+n == q is undef

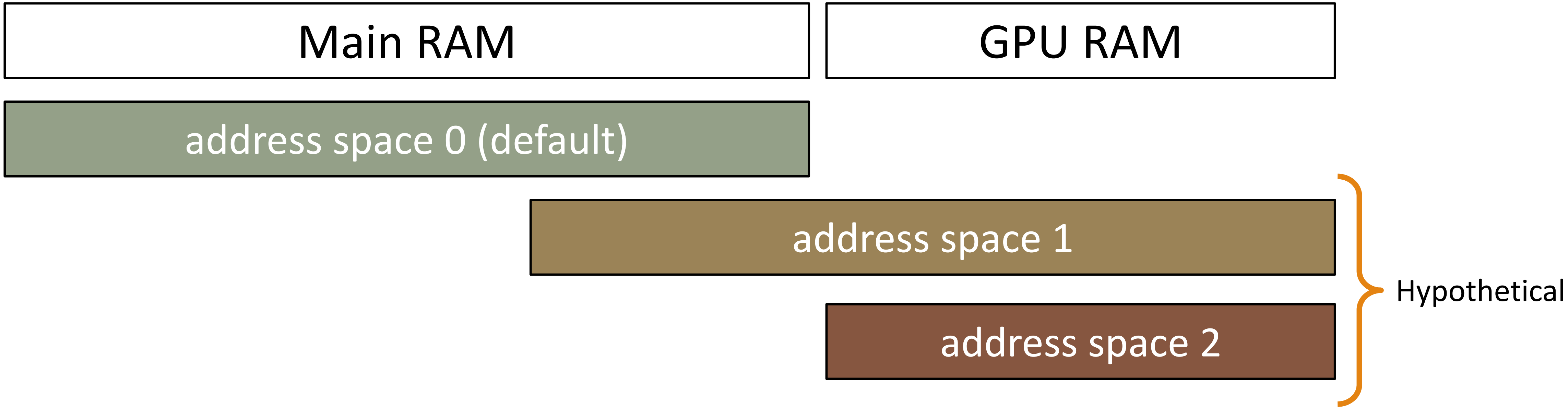
Consequences of Undef Ptr Comparison

```
char *p = ...;
char *q = ...;

if (p == q) {
   // p and q equal or
   // p+n == q (undef)
}
```

- GVN for pointers: not safe to replace p with q unless:
  - q is nullptr (~50% of the cases)
  - q is inttoptr
  - Both p and q are logical and are dereferenceable
  - …

Address Spaces

- Virtual view of the memory(ies)
- Arbitrary overlap between spaces
- (int*)0 not dereferenceable in address space 0



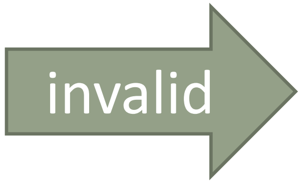
Pointer Subtraction

- Implemented as (int)p – (int)q
- Correct, but loses information vs p – q (only defined for p,q in same object)
- Analyses don’t recognize this idiom yet

Malloc and ICmp Movement

- ICmp moves freely
- It’s only valid to compare pointers with overlapping liveness ranges
- Potentially illegal to trim liveness ranges

```
char *p = malloc(4);
char *q = malloc(4);

// valid
if (p == q) { ... }

free(p);
```



```
char *p = malloc(4);
free(p);

char *q = malloc(4);

// poison
if (p == q) { ... }
```

Summary: so far

- Two pointer types:
  - Logical (malloc/alloca): data-flow provenance
  - Physical (inttoptr): control-flow provenance

- p ≠ (int*)(int)p
- There’s no “free” GVN for pointers

Alias Analysis

Alias Analysis queries

- alias()
- getModRefInfo()

AA Query

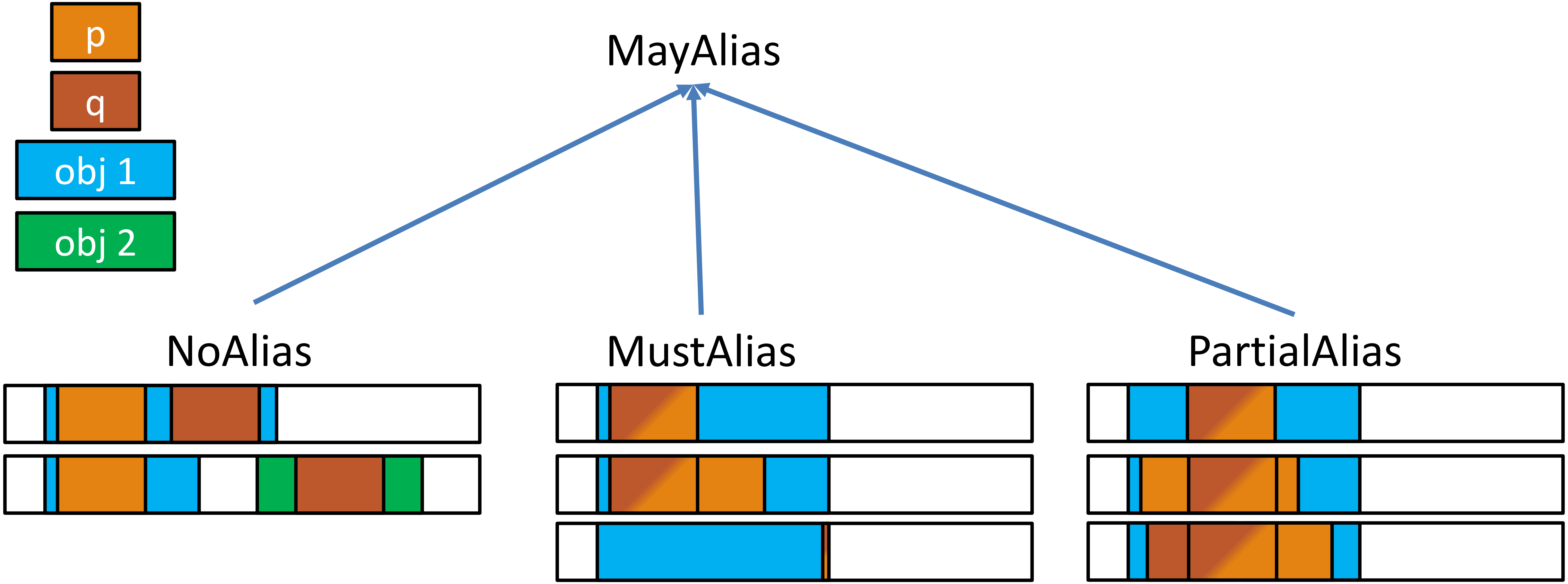
```
char *p = ...;
int  *q = ...;

*p = 0;
*q = 1;
print(*p); // 0 or 1?
```

alias(p, 1 , q, 4) = ?

alias(p, sz_p, q, sz_q)

what’s the aliasing between pointers p, q and resp. access sizes sz_p, sz_q

AA Results

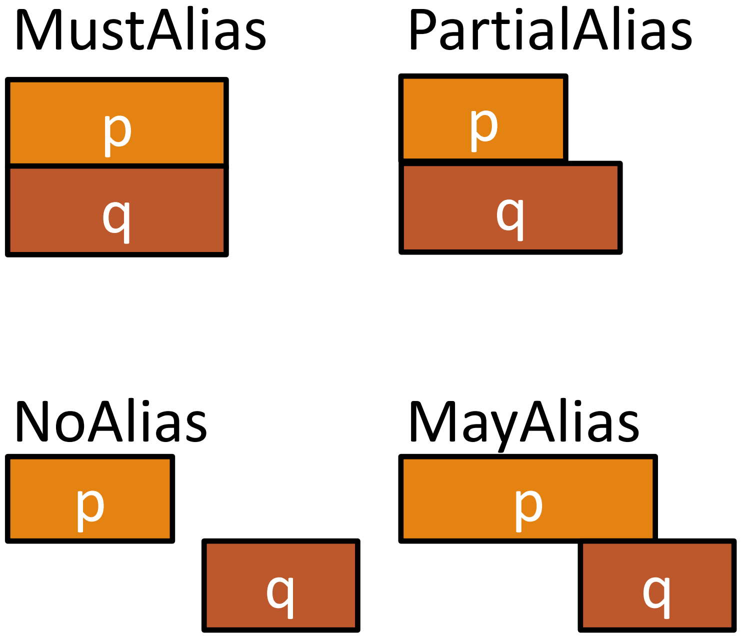


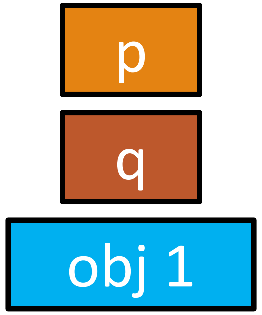
AA caveats

“Obvious” relationships between aliasing queries often don’t hold

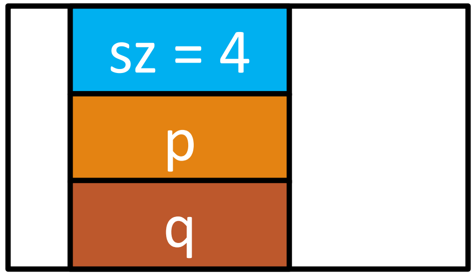
E.g. alias(p, sp, q, sq) == MustAlias doesn’t imply
alias(p, sp2, q, sq2) == MustAlias

And: alias(p, sp, q, sq) == NoAlias doesn’t imply
alias(p, sp2, q, sq2) == NoAlias





AA results

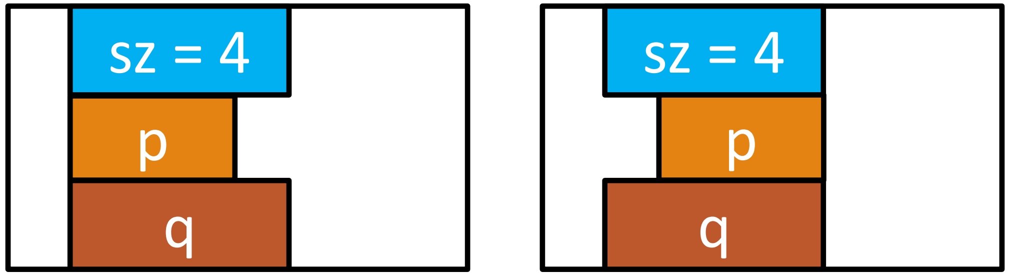


```
char *p = obj + x;
char *q = obj + y;
```

alias(p, 4, q, 4) = MustAlias

access size == object size implies idx == 0

AA results assume no UB.



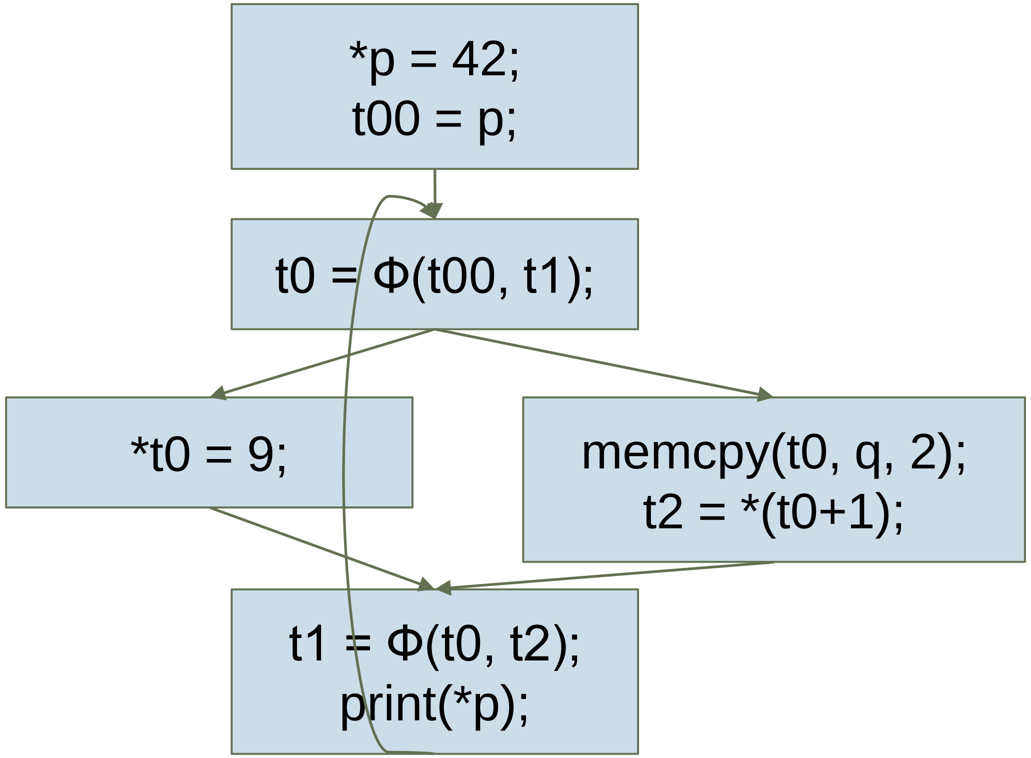
alias(p, 3, q, 4) = PartialAlias

MustAlias requires further information (e.g. know p = q)

AA results are sometimes unexpected and can be overly conservative.

AA must consider UB (PR36228)

```
i8* p = alloca (2);
i8* q = alloca (1);
```



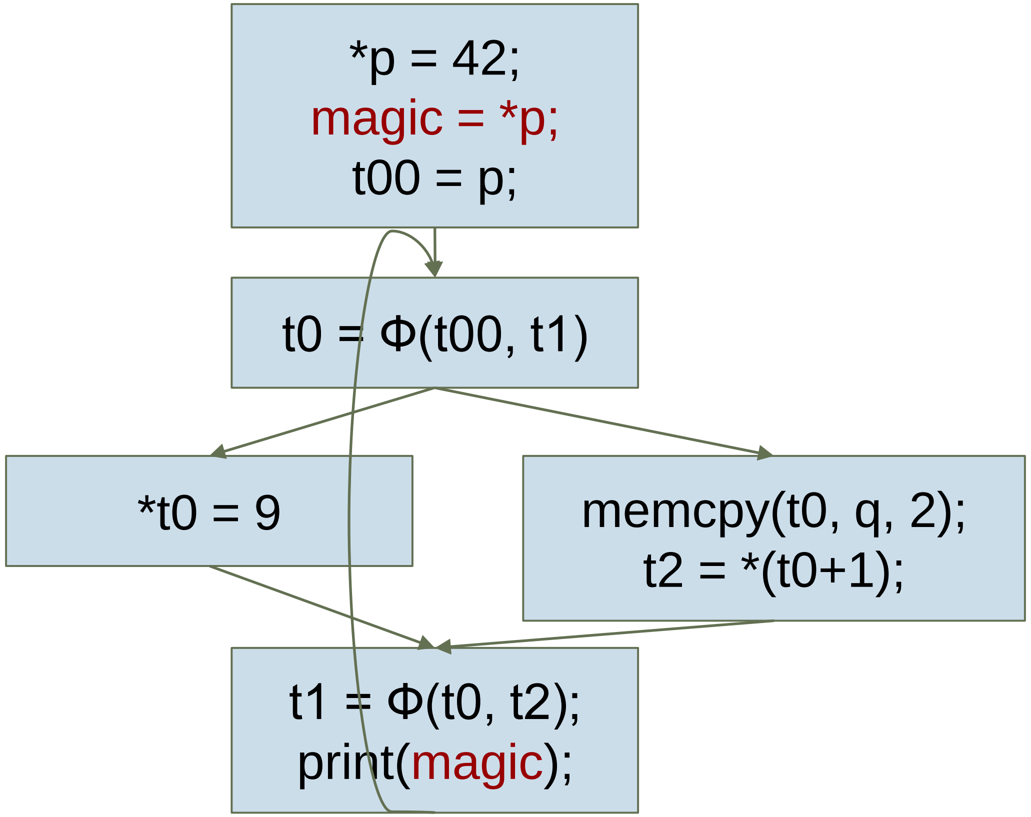
```
*p = 42;
t00 = p;
```

```
t0 = Φ(t00, t1);
```

```
*t0 = 9;
```

```
memcpy(t0, q, 2);
t2 = *(t0+1);
```

```
t1 = Φ(t0, t2);
print(*p);
```



```
*p = 42;
magic = *p;
t00 = p;
```

```
t0 = Φ(t00, t1)
```

```
*t0 = 9
```

```
memcpy(t0, q, 2);
t2 = *(t0+1);
```

```
t1 = Φ(t0, t2);
print(magic);
```

New in AA: precise access size

- Recent API changes introduced two access size types:
  - Precise: when the exact size is known
  - Upper bound: maximum size, but no minimum size guaranteed (can be 0)

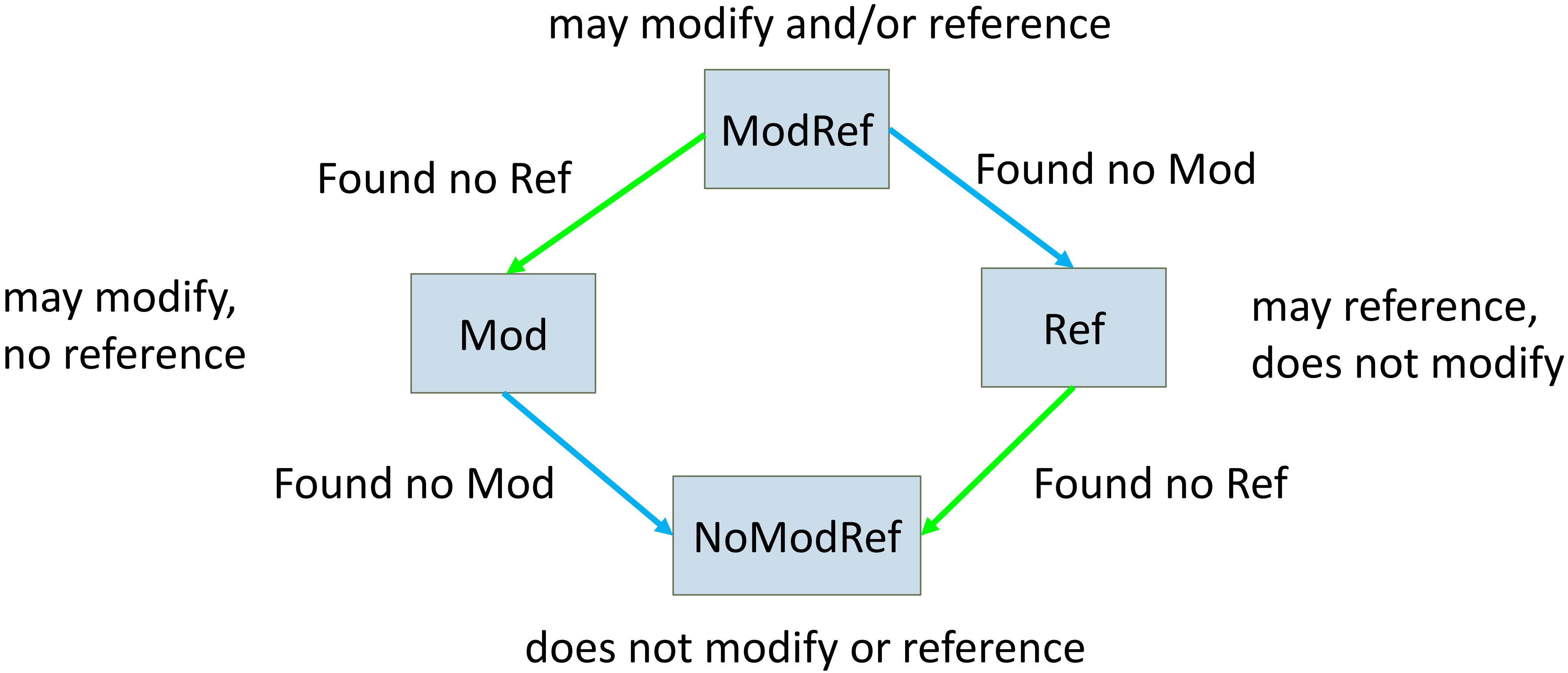
- See D45581, D44748

ModRef Analysis

ModRefInfo

- How instructions affect memory instructions:
  - Mod = modifies / writes
  - Ref = accesses / reads

ModRefInfo Overview



may modify and/or reference

ModRef

Found no Ref

Found no Mod

may modify,
no reference

Mod

Ref

may reference,
does not modify

Found no Mod

Found no Ref

NoModRef

does not modify or reference

ModRef Example

```
declare i32 @g(i8*)
declare i32 @h(i8*) argmemonly
```

```
define void @f(i8* %p) {
  %1 = call i32 @g(i8* %p)           ; ModRef %p
  store i8 0, i8* %p                 ; Mod %p (no Ref %p)
  %2 = load i8, i8* %p               ; Ref %p (no Mod %p)

  %3 = call i32 @g(i8* readonly %p)  ; ModRef %p  (%p may be a global)
  %4 = call i32 @h(i8* readonly %p)  ; Ref %p     (h only accesses args)

  %a = alloca i8
  %5 = call i32 @g(i8* readonly %a)  ; ModRef %a (tough %a doesn’t escape)
```

New ModRefInfo API

- Checks:
  - isNoModRef
  - isModOrRefSet
  - isModAndRefSet
  - isModSet
  - isRefSet

- Retrieve ModRefInfo from FunctionModRefBehavior
  - createModRefInfo

- New value generators:
  - setMod
  - setRef
  - setModAndRef
  - clearMod
  - clearRef

  - unionModRef
  - intersectModRef

Using the New ModRef API

```
Result == MRI_NoModRef
```

→

```
isNoModRef(Result)
```

```
if (onlyReadsMemory(MRB))
  Result = ModRefInfo(Result & MRI_Ref);
else if (doesNotReadMemory(MRB))
  Result = ModRefInfo(Result & MRI_Mod);
```

→

```
if (onlyReadsMemory(MRB))
  Result = clearMod(Result);
else if (doesNotReadMemory(MRB))
  Result = clearRef(Result);
```

```
Result = ModRefInfo(Result & ...);
```

→

```
Result = intersectModRef(Result, ...);
```

Using the New ModRef API

```
ModRefInfo ArgMask = getArgModRefInfo(CS1, CS1ArgIdx);
ModRefInfo ArgR = getModRefInfo(CS2, CS1ArgLoc);

if (((ArgMask & MRI_Mod) != MRI_NoModRef &&
     (ArgR & MRI_ModRef) != MRI_NoModRef) ||
     ((ArgMask & MRI_Ref) != MRI_NoModRef &&
     (ArgR & MRI_Mod) != MRI_NoModRef)) {
      ...
}
```

```
ModRefInfo ArgModRefCS1 = getArgModRefInfo(CS1, CS1ArgIdx);
ModRefInfo ModRefCS2 = getModRefInfo(CS2, CS1ArgLoc);

if ((isModSet(ArgModRefCS1) && isModOrRefSet(ModRefCS2)) ||
    (isRefSet(ArgModRefCS1) && isModSet(ModRefCS2))) {
     …
}
```

Why have MustAlias in ModRefInfo?

- AliasAnalysis calls are expensive!
- Avoid double AA calls when ModRef + alias() info is needed.

- Currently used in MemorySSA

Example: promoting call arguments

- Call `foo` is `argmemonly` a
- `isMustSet(getModRefInfo(foo, a))`
- `getModRefInfo(foo, a)` can have both Mod and Ref set.

```
char *a, *b;


for {
  foo (a);
  b = *a + 5;
  *a ++;
}
```

```
char *a, *b, tmp;
// promote to scalar
tmp = *a;
for {
  foo (&tmp);
  b = tmp + 5;
  tmp ++;
}
*a = tmp;
```

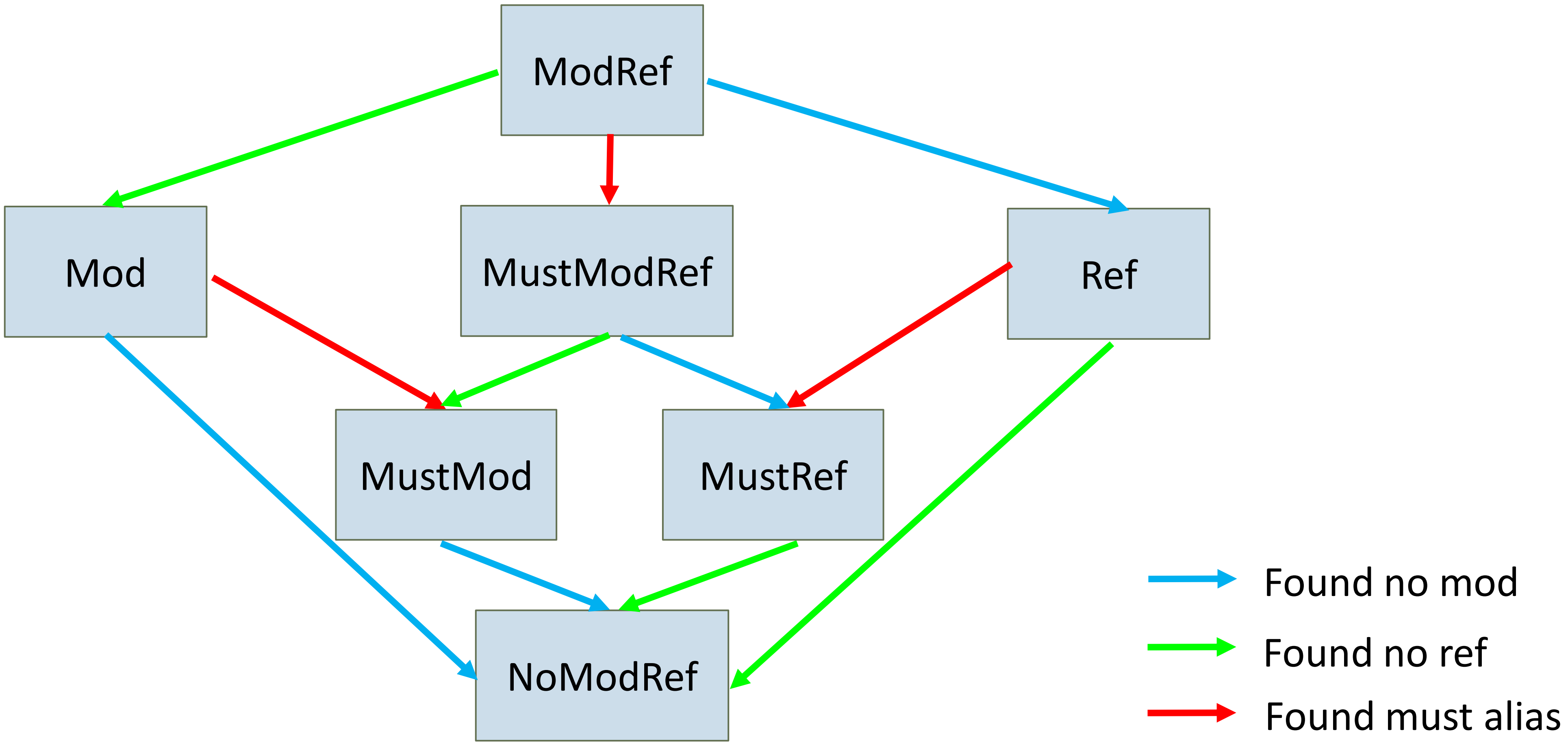
MustAlias can include NoAlias for calls?

- Call `foo` is `argmemonly` a
- `isMustSet(getModRefInfo(foo, a))`
- `getModRefInfo(foo, a)` can have both Mod and Ref set.

```
char *a, *b;
char *c = malloc;


for {
  foo (a, c);
  b = *a + 5;
  *a ++;
}
```

```
char *a, *b, tmp;
char *c = malloc; // noalias(a, c)
// promote to scalar
tmp = *a;
for {
  foo (&tmp, c);
  b = tmp + 5;
  tmp ++;
}
*a = tmp;
```

New ModRef Lattice



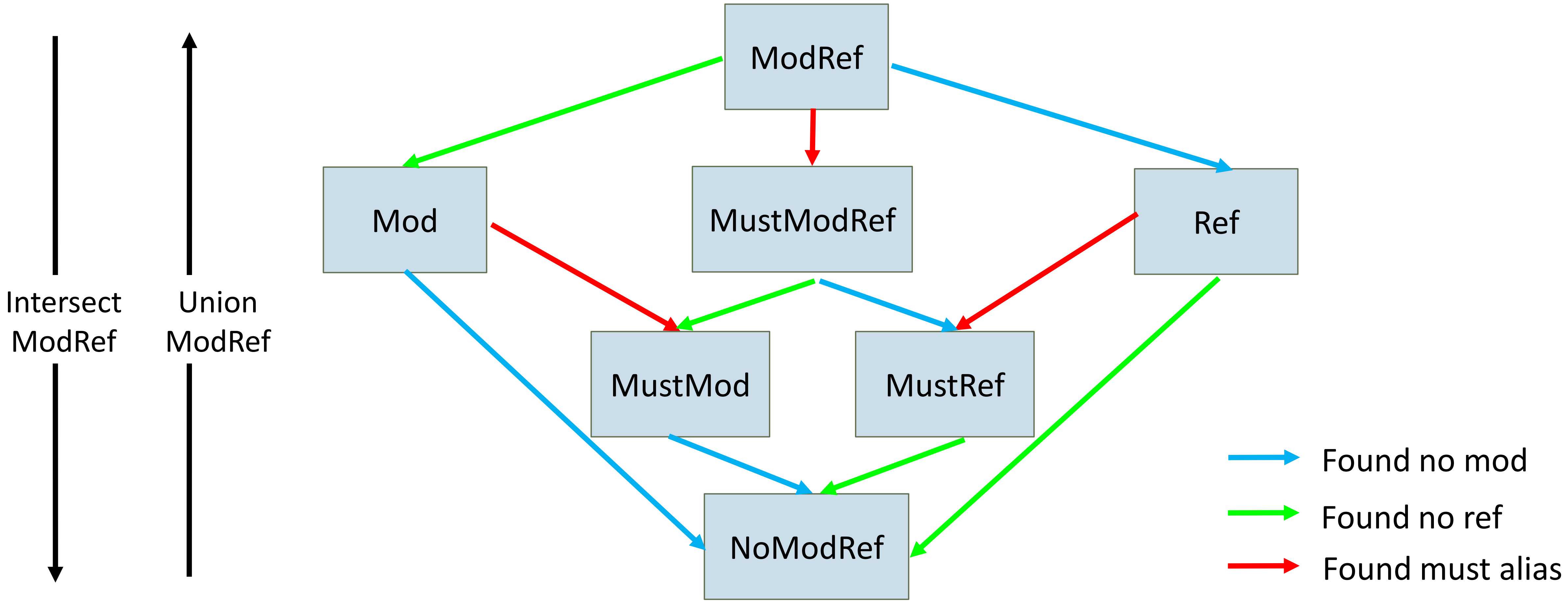
Common Misconceptions of Must in ModRefInfo

- MustMod = may modify, must alias found, NOT must modify
    - E.g., foo has readnone attribute => ModRef(foo(a), a) = NoModRef.
- MustRef = may reference, must alias found, NOT must reference
- MustModRef = may modify and may reference, must alias found, NOT must modify and must reference

Key takeaways

- ModRef is the most general response: may modify or reference
- Mod is cleared when we’re sure a location is not modified
- Ref is cleared when we’re sure a location is not referenced
- Must is set when we’re sure we found a MustAlias
- NoModRef means we’re sure location is neither modified or referenced, i.e. written or read
    - The “Must” bit in the ModRefInfo enum class is provided for completeness, and is not used

New ModRef Lattice



Intersect ModRef

Union ModRef

ModRef

Mod

MustModRef

Ref

MustMod

MustRef

NoModRef

Found no mod

Found no ref

Found must alias

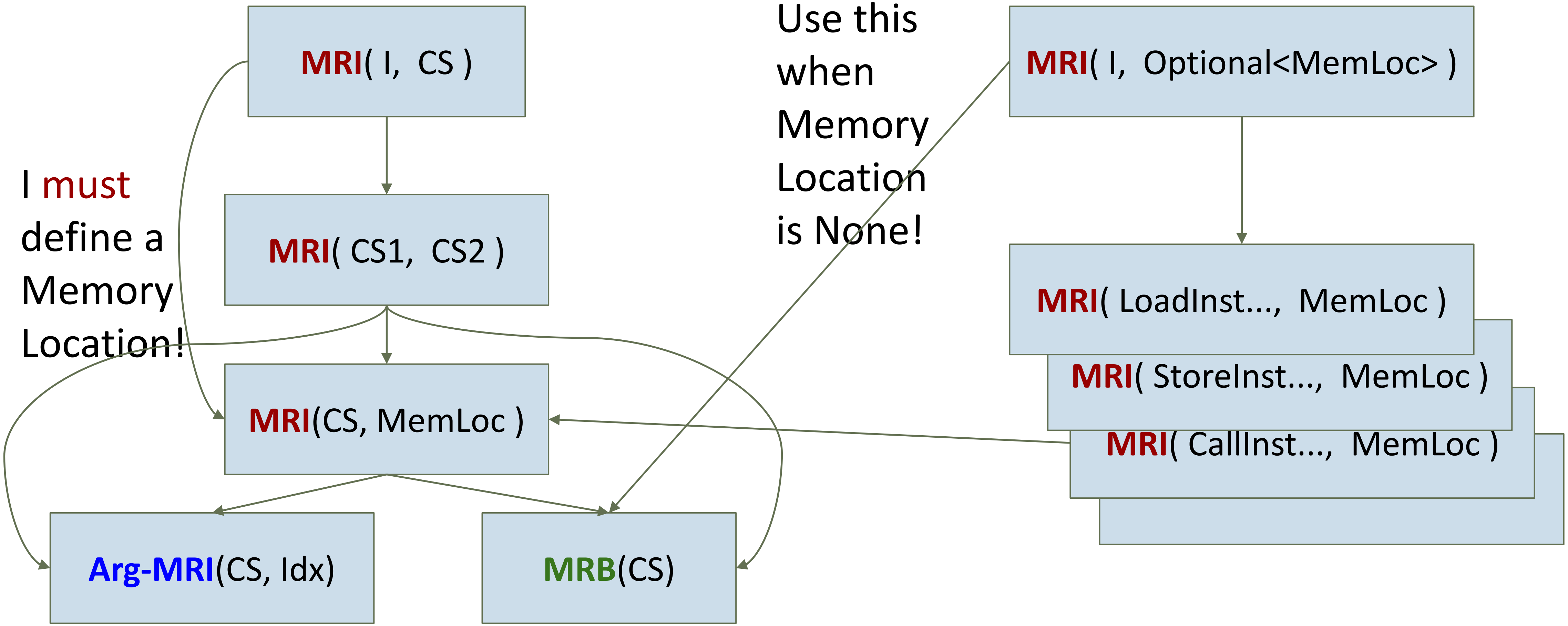
Disclaimers / Implementation details

- GlobalsModRef relies on a certain number of bits available for alignments. To mitigate this, Must info is being dropped.
- FunctionModRefBehavior still relies on bit-wise operations. Changes similar to ModRefInfo may happen in the future.

ModRefInfo API overview

- getModRefBehavior (CallSite) → MRB
- getArgModRefInfo (CallSite, ArgIndex) → Arg-MRI
- getModRefInfo(...) → MRI

ModRefInfo API overview


MRI(I, CS)
MRI(CS1, CS2)
MRI(CS, MemLoc)
Arg-MRI(CS, Idx)
MRB(CS)
MRI(I, Optional<MemLoc>)
MRI(LoadInst..., MemLoc)
MRI(StoreInst..., MemLoc)
MRI(CallInst..., MemLoc)

I must define a Memory Location!

Use this when Memory Location is None!

Summary

Summary: Pointers ≠ Integers

- Two pointer types:
  - Logical (malloc/alloca): data-flow provenance
  - Physical (inttoptr): control-flow provenance

- AA: what’s the NoAlias/MustAlias/PartialAlias/MayAlias relation between 2 memory accesses?
- ModRef: what’s the (Must)NoModRef/Mod/Ref/ModRef relation between 2 operations?

- p ≠ (int*)(int)p
- There’s no “free” GVN for pointers
- Use new pointer analyses APIs to reduce compilation time